

# The Constrained $E_6$ SSM

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We discuss the predictions of a constrained version of the exceptional supersymmetric standard model (cE6SSM), with a universal high energy soft scalar mass, soft trilinear coupling and soft gaugino mass. The spectrum includes a light gluino, a light wino-like neutralino and chargino pair and a light bino-like neutralino, with other sparticle masses except the lighter stop being much heavier. We also discuss scenarios with an extra light exotic colour triplet of fermions and scalars and a TeV scale  $Z'$ , which lead to early exotic physics signals at the LHC.

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The Exceptional Supersymmetric Standard Model ( $E_6$ SSM) [1] is inspired by Grand Unification under the gauge group  $E_6$ . It does not contain the  $E_6$  symmetry, but supposes a breaking  $E_6 \rightarrow SO(10) \times U(1)_\psi$ , followed by  $SO(10) \rightarrow SU(5) \times U(1)_\chi$ , to give the subgroup  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'$  at low energies. To allow heavy right-handed neutrinos (facilitating the see-saw mechanism), the remaining  $U(1)'$  at low energy is the combination  $U(1)' = U(1)_\chi \cos \theta + U(1)_\psi \sin \theta$  with  $\theta = \arctan \sqrt{15}$ , which keeps the right-handed neutrinos sterile.

The particle content forms a complete 27 representation of  $E_6$  for each generation, cancelling anomalies automatically. The  $27_i$  decomposes under the  $SU(5) \times U(1)_N$  subgroup of  $E_6$  as

$$27_i \rightarrow (10, 1)_i + (5^*, 2)_i + (5^*, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i, \quad (1)$$

where bracketed quantities are the  $SU(5)$  representation and  $U(1)_N$  charge ( $\times \sqrt{40}$ ) with  $i$  a family index. Ordinary SM quarks and leptons are assigned to  $(10, 1)_i + (5^*, 2)_i$ , right-handed neutrinos  $N_i^c$  appear in  $(1, 0)_i$ , and  $(1, 5)_i$  provides singlet fields ( $S_i$ ) that carry non-zero  $U(1)_N$  charges and survive down to the EW scale. There are three pairs of  $SU(2)$ -doublets ( $H_i^d$  and  $H_i^u$ ) in  $(5^*, -3)_i$  and we identify the third generation with the MSSM Higgs doublets; the other two do not get VEVs and we refer to them as “inert”. These multiplets also contain colour triplets of exotic quarks ( $D_i$  and  $\bar{D}_i$ ). The model also requires superfields  $H'$  and  $\bar{H}'$  from extra incomplete representations to ensure gauge coupling unification (see Ref. [2] for an alternate unification scenario).

Extra symmetries are required to prevent unwanted flavour changing neutral currents and proton decay. To suppress flavour changing neutral currents, one postulates a  $Z_2^H$  symmetry under which all superfields except the third generation Higgs fields are odd. This can only be an approximate symmetry, otherwise the exotics would not be able to decay. To prevent rapid proton decay, a generalisation of R-parity is imposed. If the Higgs, exotic quarks and quark superfields are even under a discrete  $Z_2^L$  symmetry while the lepton superfields are odd, we will call this Model I and the superpotential is invariant with respect to a  $U(1)_B$  global symmetry. The exotic  $\bar{D}_i$  and  $D_i$  are then identified as diquark and anti-diquark, i.e.  $B_D = -2/3$  and  $B_{\bar{D}} = 2/3$ . Alternatively (model II), the exotic quarks and the lepton superfields could be odd under  $Z_2^B$  whereas the others superfields remain even. In this case the  $\bar{D}_i$  and  $D_i$  are leptoquarks.

Integrating out the heavy right-handed neutrinos, and assuming a hierarchical structure of Yukawas, the superpotential becomes approximately,

$$W_{E_6SSM} \simeq \lambda_i S_3 (H_i^d H_i^u) + \kappa_i S_3 (D_i \bar{D}_i) + h_t (H_3^u Q) t^c + h_b (H_3^d Q) b^c + h_\tau (H_3^d L) \tau^c + \mu' (H' \bar{H}'), \quad (2)$$

where  $i = 1, 2, 3$  and  $\lambda_i, \kappa_i$  are dimensionless couplings. The above ignores small  $Z_2^H$  violating terms such as  $g_{ijk} D_i (Q_j Q_k)$  which are unimportant for production, but may be important for decay.

The  $E_6$ SSM has 43 new parameters (14 of which are phases) compared to the MSSM, so it is useful to consider a constrained model, where the parameters unify at the GUT scale,  $M_X$ . In the constrained  $E_6$ SSM ( $cE_6$ SSM), soft scalar masses are set to  $m_0$ , gaugino masses are set to  $M_{1/2}$  and trilinear scalar couplings are set to  $A_0$ , at the scale  $M_X$  [3, 4]. It is thus characterised by the parameters  $\lambda_i(M_X), \kappa_i(M_X), h_t(M_X), h_b(M_X), h_\tau(M_X), m_0, M_{1/2}$  and  $A_0$ .

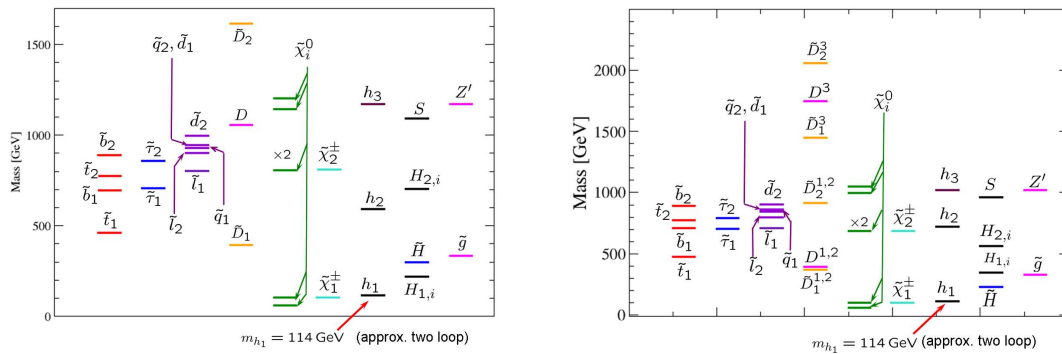
To calculate the low energy spectrum, we derived two-loop renormalisation group equations (RGEs) for gauge and Yukawa couplings, two-loop RGEs for  $M_a(Q)$  and  $A_i(Q)$  and one-loop RGEs for  $m_i^2(Q)$ . We implemented these into a modified version of SOFTSUSY 2.0.5 [5]. The

gauge and Yukawa couplings are independent of the soft SUSY breaking parameters so are determined first. The Higgs VEVs, third generation Yukawas and gauge couplings (except  $g'_i$ ) are input at the low energy scale, while  $\kappa_i(M_X)$ ,  $\lambda_i(M_X)$  are high scale inputs. We insist on gauge coupling unification, and iterate until everything is consistent. The low energy SUSY breaking parameters are determined semi-analytically as (linear or quadratic) functions of  $A_0$ ,  $M_{1/2}$  and  $m_0$ . The coefficients of each term are unknown analytically but are determined numerically. We obtain values for  $m_0$ ,  $M_{1/2}$  and  $A_0$  that are consistent with EWSB by imposing minimisation conditions on the one-loop effective Higgs potential (obtaining up to four solutions for each set of Yukawa couplings), and then calculate the mass spectrum. Although correct EWSB is not guaranteed, there are always solutions with real  $A_0$ ,  $M_{1/2}$  and  $m_0$  for sufficiently large  $\kappa_i$ .  $\kappa_i$  couples the singlet to a large number of coloured fields, efficiently driving its squared mass negative to trigger symmetry breaking.

To avoid conflict with experiment we impose:  $m_h \geq 114$  GeV; sleptons and charginos are heavier than 100 GeV; squarks and gluinos have masses above 300 GeV and the  $Z'$  boson has a mass larger than 861 GeV. We also impose bounds on the exotic quarks and squarks from the HERA experiments, by requiring them to be heavier than 300 GeV. We require the inert Higgs and inert Higgsinos are heavier than 100 GeV due to LEP bounds. Finally, we impose some theoretical constraints: the lightest SUSY particle (LSP) should be a neutralino and we restrict the GUT scale Yukawa couplings to be less than 3 to ensure applicability of perturbation theory.

To investigate the phenomenology, we fixed values of  $\tan\beta = 3, 10, 30$  and scanned over  $s$ ,  $\kappa$ ,  $\lambda$ , determining values of the soft mass parameters  $A_0$ ,  $M_{1/2}$  and  $m_0$  consistent with the correct breakdown of electroweak symmetry. We found that  $m_0 > M_{1/2}$  for each value of  $s$  and also that lower  $M_{1/2}$  is weakly correlated with lower  $s$  and thus lower  $Z'$  masses. The low energy gaugino masses are driven by RG running to be small, so the lightest SUSY states are generally a light gluino of mass  $\sim M_3$ , a light wino-like neutralino and chargino pair of mass  $\sim M_2$ , and a light bino-like neutralino of mass  $\sim M_1$ , which are typically all much lighter than the Higgsino masses of order  $\mu = \lambda \langle S_3 \rangle$ . The squarks and sleptons are much heavier than these light gauginos.

We show two possible particle spectra in Fig. 1 (see Ref. [3] for the explicit parameters used). The light gauginos ensure that pair production of  $\chi_2^0\chi_2^0$ ,  $\chi_2^0\chi_1^\pm$ ,  $\chi_1^\pm\chi_1^\mp$  and  $\tilde{g}\tilde{g}$  should always be



**Figure 1:** Spectra for two  $cE_6$ SSM scenarios. For explicit parameters, see Ref.[3]

possible at the LHC. The gluinos are relatively narrow states with width  $\propto M_g^5/m_q^4$ , and decay via  $\tilde{g} \rightarrow q\tilde{q}^* \rightarrow q\bar{q} + E_T^{\text{miss}}$ , resulting in an enhancement of the cross section  $pp \rightarrow q\bar{q}q\bar{q} + E_T^{\text{miss}} + X$ .

For the left-hand scenario, we have taken  $\kappa_1 = \kappa_2 = \kappa_3$  at the GUT scale and large enough to trigger EWSB, resulting in heavy and degenerate exotic quarks. Nevertheless, due to mixing, we find a light exotic coloured scalar with mass 393 GeV. For the right-hand scenario, we have instead set  $\kappa_3 \gg \kappa_{1,2}$ , allowing for rather light exotic quarks of 391 GeV.

Assuming  $D_i$  and  $\bar{D}_i$  couple most strongly to the third generation, the lightest  $D_i$  and  $\bar{D}_i$  decay into  $\tilde{t}b$ ,  $\tilde{t}\bar{b}$ ,  $\tilde{t}\tilde{b}$ ,  $\tilde{t}\bar{\tilde{b}}$  (if diquarks) or  $\tilde{t}\tau$ ,  $t\tilde{\tau}$ ,  $\tilde{b}\nu_\tau$ ,  $b\tilde{\nu}_\tau$  (if leptoquarks). This leads to a substantial enhancement of either  $pp \rightarrow \tilde{t}\tilde{b}\bar{b} + E_T^{\text{miss}} + X$  (if diquarks) or  $pp \rightarrow \tilde{t}\tilde{\tau}\bar{\tau} + E_T^{\text{miss}} + X$  or  $pp \rightarrow \tilde{b}\bar{b} + E_T^{\text{miss}} + X$  (if leptoquarks). Therefore light leptoquarks should produce a strong signal with low SM background at the LHC. For example, for a  $D$  mass of 400 GeV, the production cross-section  $pp \rightarrow D\bar{D}$  is 17.4 pb. The observation of the  $D$  fermions should be possible if they have masses below about 1.5-2 TeV [1]. The exotic scalars ( $\tilde{D}_i$  and  $\bar{\tilde{D}}_i$ ) may be produced singly and decay into quark–quark (if diquarks) or quark–lepton (if leptoquarks) without missing energy. Recent Tevatron searches for dijet resonances rule out scalar diquarks with mass less than 630 GeV. However, scalar leptoquarks may be as light as 300 GeV since they are pair produced through gluon fusion. They then decay, e.g.  $\tilde{D} \rightarrow t\tau$ , leading to an enhancement of  $pp \rightarrow \tilde{t}\tilde{\tau}\bar{\tau}$ .

A light inert Higgs decays via terms analogous to the Yukawa interactions of normal Higgs superfields, leading to decays such as  $H_{1,i}^0 \rightarrow b\bar{b}$  and  $H_{1,i}^- \rightarrow \tau\bar{\nu}_\tau$ . Similar couplings govern inert Higgsino decays resulting in e.g.  $\tilde{H}_i^0 \rightarrow \tilde{t}\tilde{t}^*$ ,  $\tilde{H}_i^0 \rightarrow \tilde{\tau}\tilde{\tau}^*$ ,  $\tilde{H}_i^+ \rightarrow \tilde{t}\tilde{b}^*$  and  $\tilde{H}_i^- \rightarrow \tilde{\tau}\tilde{\nu}_\tau^*$ .

To conclude, the  $cE_6$ SSM is a well motivated model with a distinctive spectrum: a light gluino (much lighter than the squarks), and new exotic states such as a  $Z'$  and colour triplet fermions and scalars. If these new states are light enough, they could be found with early LHC data, leading to a revolution in particle physics, and pointing towards an underlying high energy  $E_6$  gauge structure.

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